Method of Estimating the Values of Reliability Indicators of Objects with Variable Structure

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Abstract

The article proposes to improve the method of estimating the values of operating time on failure, the average recovery time and the coefficient of readiness of radio equipment with variable structure. The essence of improvement is to take into account the operating time of the individual components of the product in the possible modes of use for its intended purpose. In known works, this fact is not taken into account, so the results of calculations give an underestimation of the values of reliability indicators, which, in turn, leads to an overestimation of the cost of the product. An example of using the method is given and the effect of its application is shown.

Keywords

Reliability indicators, multi-mode objects, variable structure, operating time on failure, average recovery time.

1. Introduction

Modern research in the field of reliability theory of complex technical systems is aimed at creating objects with specified values of reliability indicators through the introduction of redundancy of the least reliable structural elements, and the production of so-called "absolutely reliable systems" in which the readiness factor $A \geq 0.997$ [1–5] (in some cases, for example, for interplanetary spacecraft, robots to study other planets). In addition, special attention is paid to the development of software-controlled radio equipment and systems, which also affects their reliability [4–7]. However, the complexity of modern radio equipment and the density of installation is constantly increasing: only in the radio stations of the tactical level of control over the past thirty years, the number of elements and the density of installation has increased more than six times [8]. At the same time, the requirements for the value of failure time and the average recovery time of these products have not changed.

Modern foreign sources consider various aspects of ensuring the reliability of electronic means - from improving the quality of the element base to predicting changes in the values of reliability over time, but methods for assessing the reliability of objects with variable structure are also not considered [9–15].

Thus, the task arises to ensure the required level of reliability of products while minimizing their cost. To solve it, it is necessary to improve the existing methods of calculating the values of reliability of complex technical objects, taking into account their properties: multi-mode, multifunctionality, the presence of redundancy, which leads to changes in the structure of the object during its intended use. Currently, there are not only practical but also theoretical methods for calculating the efficiency of systems with a variable structure, which can change randomly at

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short intervals. The change in structure always occurs depending on the change in the functions performed by the system [1, 2].

2. Forming the Purpose

The purpose of the article is to improve the method of estimating the values of reliability indicators of objects with a variable structure, taking into account the operating time of individual sets of elements in possible modes of use for their intended purpose.

3. Mathematical Model

Approximate calculation of the reliability of radio-electronic means (REM) without taking into account the property of their multi-mode is performed under the following assumptions:

- Failures of elements are independent.
- Failure of at least one element entails the failure of the equipment.
- Intensity of element failures does not depend on time, i.e. λ_i = const.
- Elements operate in typical (nominal) modes.
- Elements of the same type are equally reliable.

The second condition practically means that redundancy is not applied in the equipment, and elements that perform auxiliary functions should be excluded from the calculations. In other words, in the approximate calculation, it is assumed that all elements of the equipment are connected in series, with both complete and partial failure of any element leading to equipment failure.

Means of various purposes are continuously developing and improving in the direction of improving quality indicators by consumer requirements through the introduction of new schematic and design solutions, as well as the use of modern element base. This causes a corresponding complication for products, which does not lead to an improvement in the values of their reliability indicators. Therefore, the issue of ensuring the required level of reliability of modern electronic means is very important for both manufacturers and consumers.

There are known methods of ensuring the required values of reliability indicators of radio-electronic means by reserving the least reliable structural units, which increases their cost and weight, and dimensions, as well as the volume of spare tools and accessories for the implementation of current repairs by the aggregate method. The directions of automation of calculations of reliability indicators of electronic means and their changes over time also investigated.

A promising direction in the development of radio-electronic means of the communication industry is the introduction of software-controlled means, the quality of which also affects the reliability of individual products and the communication system as a whole.

The value of the complex indicator of the reliability of radio-electronic means—their availability factor—is significantly affected not only by the MTBF, but also by the average recovery time, so in special technical literature, research, and dissertation work, attention is paid to improving the quality of diagnostic support for repair. During the quantitative assessment of the values of reliability indicators of electronic means, which are determined by design tasks, do not take into account the property of multi-mode, which leads to changes in the structure of objects during their intended use.

At present, there are not only engineering methods but also theoretical developments of reliability analysis of technical systems with changing structure, which is due to its multi-functionality and multimode, when in separate modes of operation the corresponding sets of elements are used. Multi-mode properties used in the development of diagnostic software, but when assessing reliability, it is traditionally believed that all elements of the object operate simultaneously, and this significantly underestimates the MTBF.

Today, in modern domestic and foreign publications on topical issues of the reliability of complex technical objects and systems, some directions for increasing the values of their reliability indicators considered. However, these publications do not consider the issues of complex consideration of the reliability of individual components of software-controlled multi-mode communication facilities with changing structures during the assessment of their performance in both the design process and refinement during trial operation.

There is a problem with increasing the accuracy of a quantitative assessment of the reliability of radio-electronic means with a change in structure by using a new model that takes into account the operating time of individual elements of the object in various modes of operation and increases the accuracy of calculations taking into account the peculiarities of construction and intended use of these objects.

The development task standardizes the mean time between failures and the average recovery time of existing, modernized, and prospective multimode radio electronic devices. Therefore, during the design, it is mandatory to perform a reliability calculation with a quantitative assessment of all reliability indicators, which are then checked during trial operation.

Communication equipment belongs to the class of objects with changing structures, which can be single and multifunctional, multimode with a fixed or arbitrary change of operating modes.

To model these objects, the well-known mathematical apparatus of set theory was used, but only during the development of diagnostic software. Set-theoretic models allow us to estimate the power of sets of elements used in separate modes of operation, as well as their interconnection.

For example, with a fixed change of modes, it is advisable to use a model of the "garland" type, when with each step the number of elements of the object increases. This leads to a decrease in MTBF and an increase in the average recovery time, which worsens the value of the complex reliability indicator - the facility availability factor.

When arbitrarily changing the operating modes of a radio receiver or radio station, it is advisable to use a set-theoretic model with intersections of subsets of elements that have a core (for example, amplifiers, power supply or generator equipment). In this case, the reliability of individual subsets of elements is significantly affected by the time of their operation in a given mode (for example, the operating time of the radio station in the "receive" mode is many times longer than in the "transmit" mode), that is, the technical resource of the elements is calculated unevenly.

To take into account this circumstance, it is proposed to apply the coefficient of use for each subset of elements in possible modes of operation of the product, which is calculated as the ratio of the operating time of a subset of elements to the total operating time of the product in all possible modes. Its value can be quantified from the analysis of the use of communication means, which is reflected in the hardware logs of communication nodes.

Consider the use of these proposals on the example of a multi-mode object, the scheme of which shown in Fig. 1. The object operates in three modes, each of which uses five of the eight total subsets of elements. This is a set-theoretic model with strong intersections of a subset of elements and a core consisting of elements 7 and 8, which are used in all modes of operation.

In the traditional approximate calculation of reliability, the minimum and maximum values of the parameter of the flow of failures of individual elements in (Z_i) are summed up, after which the limits of change and the average values of the MTBF are determined

$$T = 1 \Big/ \sum_{i=1}^{L} Z_i \,. \tag{1}$$

In this case, the real operating time of individual elements is not taken into account.

If the value of the parameter Z_{Ri} of failures of individual elements of the product is known, then for each mode of operation we obtain:

$$Z_{R1} = Z_1 + Z_4 + Z_5 + Z_7 + Z_8\,; \tag{2}$$

$$Z_{R2} = Z_2 + Z_4 + Z_6 + Z_7 + Z_8\,; \tag{3}$$

$$Z_{R3} = Z_3 + Z_5 + Z_6 + Z_7 + Z_8\,. \tag{4}$$

In this case, the MTBF of the product in each operating mode is equal:

$$T_1 = \frac{1}{Z_{R1}};\ T_2 = \frac{1}{Z_{R2}};\ T_3 = \frac{1}{Z_{R3}}. \tag{5}$$

If there is additional data on the time of operation of the product in individual modes (T_{pi}), it is possible to calculate the value of the relative utilization factor of each element accordingly:

$$u_1 = \frac{T_{p1}}{T_p};\ u_2 = \frac{T_{p2}}{T_p};\ u_3 = \frac{T_{p3}}{T_p}; \tag{6}$$

$$u_4 = \frac{T_{p1}+T_{p2}}{T_p};\ u_5 = \frac{T_{p1}+T_{p3}}{T_p};\ u_6 = \frac{T_{p2}+T_{p3}}{T_p}; \tag{7}$$

$$u_7 = 1;\ u_8 = 1; T_p = T_{p1} + T_{p2} + T_{p3}; \tag{8}$$

where T_p is the total operating time of the product in all possible modes.

This allows, taking into account the specific operating time of each element of the product, to quantify the predicted number of their failures and the product as a whole:

$$N = T_p \sum_{i=1}^{8} U_i Z_i = \sum_{i=1}^{8} Z_i T_{pi} = \sum_{i=1}^{8} \frac{T_{pi}}{T_i}\,. \tag{9}$$

Then the failure rate of the product as a whole is equal:

$$Z = \frac{N}{T_p} = \sum_{i=1}^{8} U_i Z_i\,, \tag{10}$$

where $T_{pi}/T_i = N_i$ is MTBF of individual subsets of elements, and MTBF taking into account the operating time of subsets of elements in separate modes, respectively $T = T_p / N$.

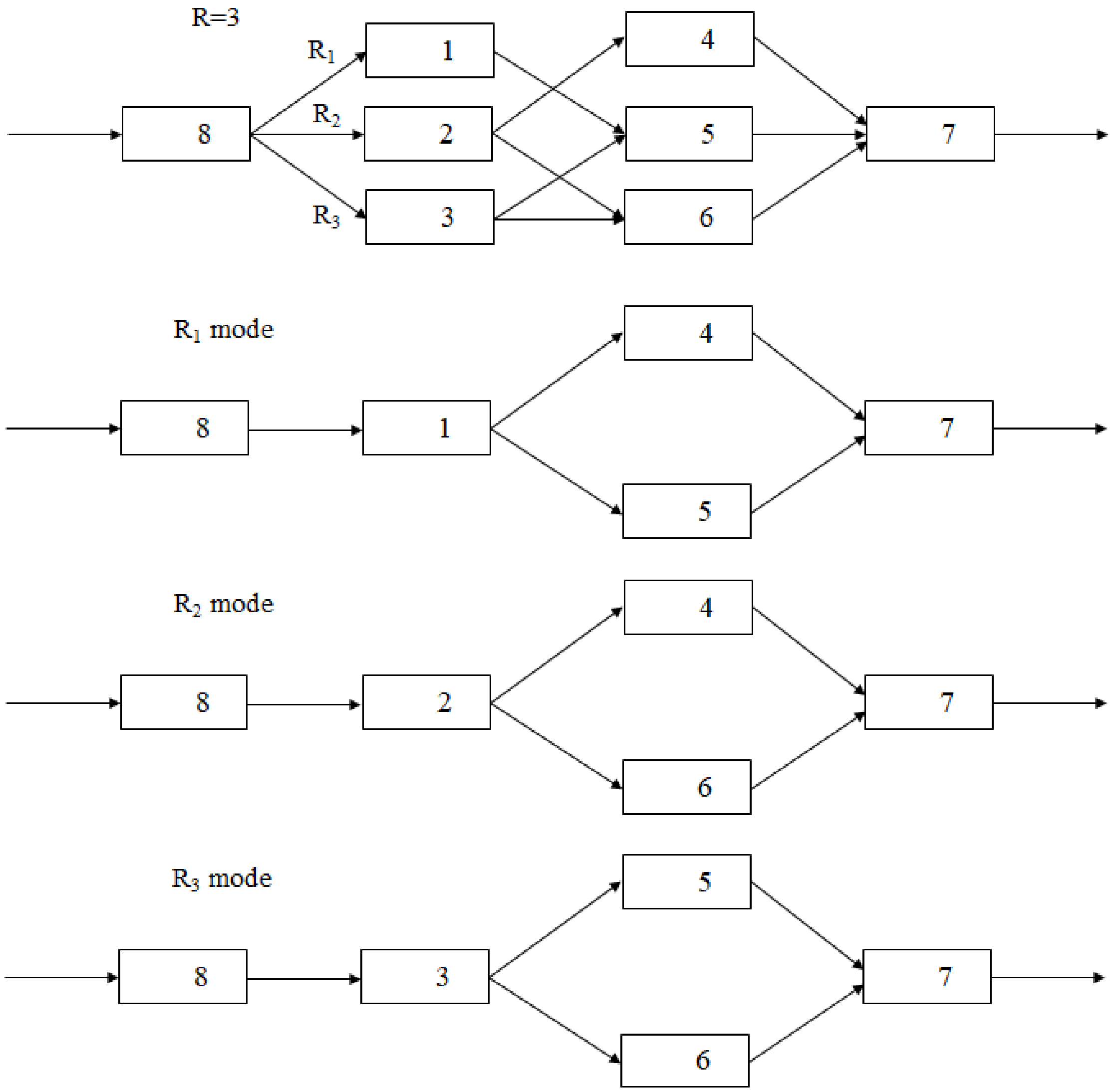

Figure 1: An example of a multi-mode technical object with a core and a strong intersection of a subset of elements

Suppose that all subsets of elements in the example under consideration are equally reliable (Z_i=Z) and in each mode of operation the product operates for the same time ($T_{pi} = T_p / 3$), then we obtain

$$u_1 = u_2 = u_3 = 1/3;$$
$$u_4 = u_5 = u_6 = 2/3; \qquad (11)$$
$$u_7 = u_8 = 1.$$

The total number of product failures during operation T_p is $N = ZT_p \sum_{i=1}^{8} U_i = 5ZT_p$, and MTBF is $T = 1/5Z$.

Under the same conditions with the traditional conditional calculation of reliability we obtain $T' = 1/8Z$, that is, the real value of MTBF of the product, taking into account its multi-mode properties, has increased several $T/'T = 1{,}6$ times, or by $[(T - T')/T']100\% = 37{,}5\%$.

Obviously, the greater the number of possible modes of operation of the product, the more accurate is the estimate of the MTBF value taking into account the multi-mode property. But, this requires additional initial data for the predicted time of operation of the product in each mode.

The MTBF of electronic equipment as a whole (T) depends on the operating time of individual parts of the product used in various operating modes (T_i), which in turn is determined by the failure rate of this subset of elements (Z_i) $T_i = 1/Z_i$.

The multi-mode property of radio electronic equipment is taken into account by introducing the coefficient of use of individual sets of elements depending on the relative time of their operation $u_i = T_{pi} / T_p; i = \overline{1, n}$; where n is the number of subsets of radio electronic equipment elements used in different modes;

T_p is total operating time of radio electronic means.

In this case, the total number of product failures over time T_p is

$$N = \sum_{i=1}^{n} \frac{T_{pi}}{T_i} = T_p \sum_{i=1}^{n} U_i Z_i , \qquad (12)$$

and the failure rate parameter of the radio electronic means as a whole is equal to

$$T = \frac{T_p}{N} = 1 \Big/ \sum_{i=1}^{n} u_i Z_i = \frac{1}{Z} ; \qquad (13)$$

where Z is parameter of the product failure rate.

Another indicator of the reliability of radio electronic means, which is standardized and set by the guiding documents, is the average recovery time T_B. It depends on the qualification of the performers (t is average time of parameter checking, and t_y is average time of fault elimination), quality of metrological and diagnostic support, power of subsets of elements used in separate modes of the product operation, and probability of their failure.

When searching for defects during the current repair by programs based on the use of conditional algorithms of the minimum form, the average number of checks

$$K_i = \ell og_2 L_i ; \; i = \overline{1, n} ; \qquad (14)$$

where K_i is the average number of inspections to find defects in a subset of elements L_i, among which it is necessary to determine the faulty one.

Average number of inspections during the current repair of the product, in general

$$K_i = \frac{1}{n} \sum_{i=1}^{n} \ \ell og_2 L_i .$$

In this case, the total number of elements of radio electronic means $L = \sum_{i=1}^{n} L_i$ provided that the elements of subsets are used only in certain modes of operation, and the average number of checks $K_i = \frac{1}{n} \sum_{i=1}^{n} \ \ell og_2 L_i$.

The probability of product failure due to a defect among the elements L_i is

$$\frac{N_i}{N} = \frac{T_{pi}}{T_i T_p \sum_{i=1}^{n} u_i Z_i} = \frac{u_i T_p}{\frac{1}{Z_i} T_p Z} = \frac{u_i Z_i}{Z} , \qquad (15)$$

while $T \sum_{i=1}^{n} u_i Z_i = 1$.

The average recovery time of the product is a discrete random variable, the mathematical expectation of which is the sum of products of its possible values (K_i) by the probability of their occurrence ($u_i z_i / z$). Then the estimated recovery time of radio electronic means (without taking into account the metrological reliability of measuring instruments) is equal to

$$T_{BP} = t_y + \frac{t}{Z} \sum_{i=1}^{n} u_i Z_i \ell og_2 L_i . \qquad (16)$$

In this case, the complex indicator of product reliability is availability factor, is equal to

$$A = \frac{T}{T + T_{BP}} =$$

$$= 1 \Big/ \left[1 + t \sum_{i=1}^{n} u_i Z_i \ell og_2 L_i + t_y \sum_{i=1}^{n} u_i Z_i \right] . \qquad (17)$$

The readiness factor $U = 1 - A$.

This expression does not take into account the probability of correct diagnosis $P = p^k$, where p is the probability of correct assessment of the result of the test of the parameter of radio electronic means, as well as the metrological reliability of measuring instruments $P(\tau)$, where τ is the period of testing of measuring instruments.

Thus, the objective function of the research is minimization of the value of the complex indicator of product reliability is availability factor with restrictions on the permissible values of MTBF (T_d) and mean time to failure (T_{vd}), determined by the guidelines, at a given mode of operation (T_{pi}, u_i), takes the form:

$$U(x) = \min U(x^*);$$

$$x^* \in \Delta; \qquad (18)$$

$$x = (L_i, u_i, T_{pi}, Z_i, n, t, t_y, P(\tau), T, T_B),$$

where x is parameters affecting product reliability; x^* is their importance in solving the problem; Δ is the range of permissible limits for changing parameter values.

Groups of uncontrollable parameters:

L_i, n , Z_i are depend on the product circuit and the reliability of the element base.

Groups of controlled parameters under operating conditions:

T_{pi}, u_i are depend on the operating product mode;

t, t_y are depend on the qualification of the performers and the conditions for restoring performance;

K is depend on the quality of diagnostic software and the form of conditional algorithms for finding defects;

$p, P(\tau)$ are depend on the measuring equipment used during the current repair to assess the values of signals at the control points of the product.

In this case, as an indicator of efficiency, it is advisable to use the relative reduction of the unavailability coefficient, the value of which is calculated using known methods (U'), compared with the one obtained by the proposed model of reliability of objects with a variable structure (U):

$$\eta = 100(U' - U)/U'\%. \quad (19)$$

The results are summarize in table 1, which is a mathematical model for estimating the values of reliability indicators of radio-electronic means with a variable structure.

The proposed model differs from the known ones by taking into account the operating time of the product in individual modes, the probability of failure in each mode of operation and the metrological reliability of measuring instruments.

The adequacy of the model is confirmed by the fact that the formulas obtained in the right column of Table. 1 with $u_i = 1$ and $P(\tau) = 1$ and without taking into account the probability of failure of subsets of elements are transformed into known expressions, which are given in the left column of Table 1. This model is the mathematical basis of the method for estimating the values of reliability indicators of objects with a variable structure.

Table 1

Mathematical model of estimation of values of reliability indicators of radio electronic means with variable structure

Indicator	Functional dependences	
	Without taking into account multimode	With taking into account multimode
Failure rate parameter	$Z' = \sum_{i=1}^{n} Z_i$	$Z = \sum_{i=1}^{n} u_i Z_i$
MTBF (mean time to failure)	$T' = 1/Z'$	$T = 1/Z$
Total number of failures	$N' = T_p \sum_{i=1}^{n} Z_i$	$N = T_p \sum_{i=1}^{n} u_i Z_i$
Estimated average recovery time	$T'_{BP} = t_y + \frac{t}{n} \sum_{i=1}^{n} \ell og_2 L_i$	$T_{BP} = t_y + \frac{t}{Z} \sum_{i=1}^{n} u_i Z_i \ell og_2 L_i$
Average number of checks	$K_i = \frac{1}{n} \sum_{i=1}^{n} \ell og_2 L_i$	
Probability of correct diagnosis	$P = p^{\kappa}$	
Average recovery time	$T'_B = \frac{T'_{BP}}{P}$	$T_B = \frac{T_{BP}}{P \cdot P(\tau)}$
Product availability factor	$A' = \frac{T'}{T' + T'_B}$	$A = \frac{T}{T + T_B}$
Coefficient of unreadiness of the product	$U' = \frac{T'_B}{T' + T'_B}$	$U = \frac{T_B}{T + T_B}$
Effect of using the model	$\eta = \frac{U' - U}{U'} \cdot 100\%$	

4. Developed Method

The purpose of the method, its essence, initial data, limitations and assumptions, as well as the result of use are shown in the block diagram of Fig. 1. The proposed mathematical apparatus is summarized in Table 1, where for the first time the coefficients of use of sets of product elements, the values of which affect all other indicators of reliability.

The block diagram of the algorithm for the implementation of the advanced method is shown in Fig. 2, where it is additionally marked: T_d is the allowable value of the product operating time to failure, T_{vd} is the allowable recovery time of the product during maintenance. The values of these indicators are in the guiding documents.

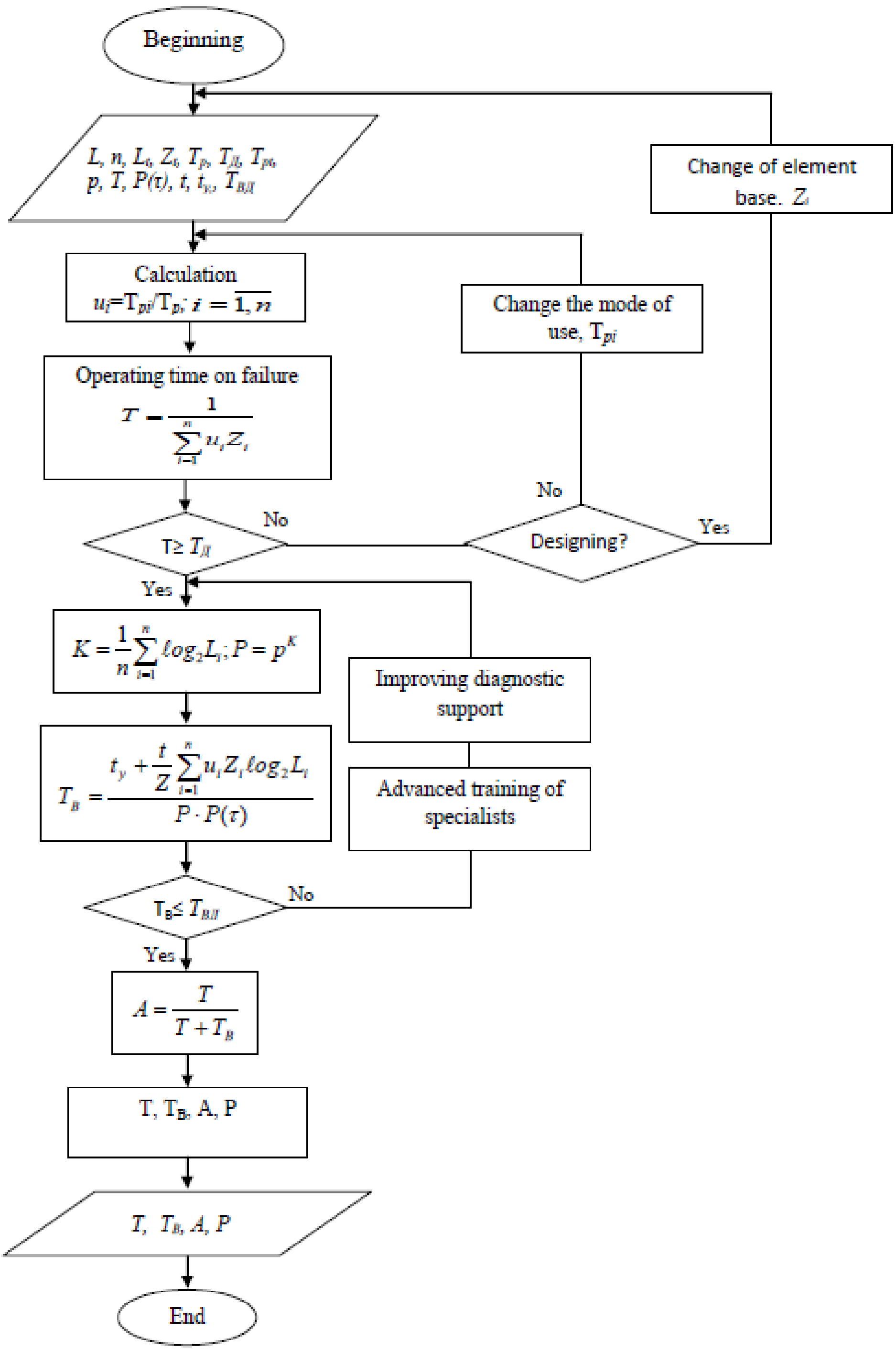

Figure 2: Block diagram of the algorithm for implementing the method of estimating the values of reliability indicators of objects with variable structure

Other source data are obtained: L, n, L_i are from the analysis of the product scheme; Z_i is calculation of the failure parameter of sets of elements according to known methods [1, 2, 5]; T_p, T_{pi} are from the analysis of the product operation mode during operation; p, $P(\tau)$ are depending on the type of measuring equipment [16–19]; t, t_y are on the analysis of work of experts of repair body depending on their qualification.

Consider the use of the results on the example of estimating the values of the reliability of the fifth generation radio [8].

Theoretical is multiple model of the radio station is shown in Fig. 3, where M_1 is the set of elements used in the "transmission" mode; M_2 is in the "reception" mode; M_{12} is core used in both modes of operation (subsystems of power supply, control and operation, generator equipment, antenna) [20, 21]. The total number of elements of the radio station is L = 4096, of which L_3 = 512 elements are used in both modes, in the "receive" mode L_2 = 3072 elements and in the "transmit" mode L_1 = 1024 elements. With $Z_1 = 307 \bullet 10^{-6}$ hours^{-1}, $Z_2 = 532 \bullet 10^{-6}$ hours^{-2}, $Z_3 = 154 \bullet 10^{-6}$ hours^{-1}.

Without taking into account the properties of multimode we obtain (n = 3):

$$Z' = \sum_{i=1}^{3} Z_i = 993 \cdot 10^{-6}\ hours^{-1}, \qquad (20)$$

the operating time for failure is equal T' =1007 hours. During the current repair of the radio station using measuring equipment with metrological characteristics p = 0.997 and $P_{(\tau)}$ = 0.96 [16–19]. If conditional diagnostic algorithms are used during the current repair, then $K = 8{,}86$. Assuming that the qualification of specialists provides t = 3,5 min and t_y = 8 min, we obtain the average recovery time $T'_{\text{В}} = 43$ min. These indicators fully meet the requirements for the reliability of similar objects $T_d \geq 1000$ hours and $T_{vd} \leq 60$ min, while A' = 0.9993 ($U' = 0{,}0007$).

The results of calculations for the same initial data according to the algorithm of Fig. 2 using the mathematical model of reliability of Table 2 taking into account the properties of the radio in two modes depending on the ratio of operating time to "receive" (U_2) or "transmit" are shown in Fig. 5–8.

Comparison of the results with the prototype (calculation of similar indicators without taking into account the multimode of the radio station) shows that at 90% of the radio station operating time in the "reception" mode (u_2 = 0,9), which often occurs in practice, we have a refinement time of 33% (T = 1507 h), the average recovery time by 14% (T_B=50 min) and a decrease in the coefficient of unpreparedness by 28% (U = 0.000548).

Table 2

Mathematical model for estimating the values of reliability indicators of objects with variable structure

Indicator	Functional dependencies
The utilization factor of the sets of elements *i*	$u_i = T_{pi}/T_p;\ i = \overline{1,n}$
Product failure flow parameter	$Z = \sum_{i=1}^{n} u_i Z_i$
Product operating time to failure	$T = 1/Z$
The average number of inspections during maintenance	$K = \frac{1}{n}\sum_{i=1}^{n} \log_2 L_i$
Probability of correct diagnosis	$P = p^K$
The average recovery time of the product	$T_B = \dfrac{t_y + \frac{t}{Z}\sum_{i=1}^{n} u_i Z_i \log_2 L_i}{P \cdot P(\tau)}$
Product readiness ratio	$A = T/T + T_B)$
The coefficient of unpreparedness of the product	$U = T_B/(T + T_B)$

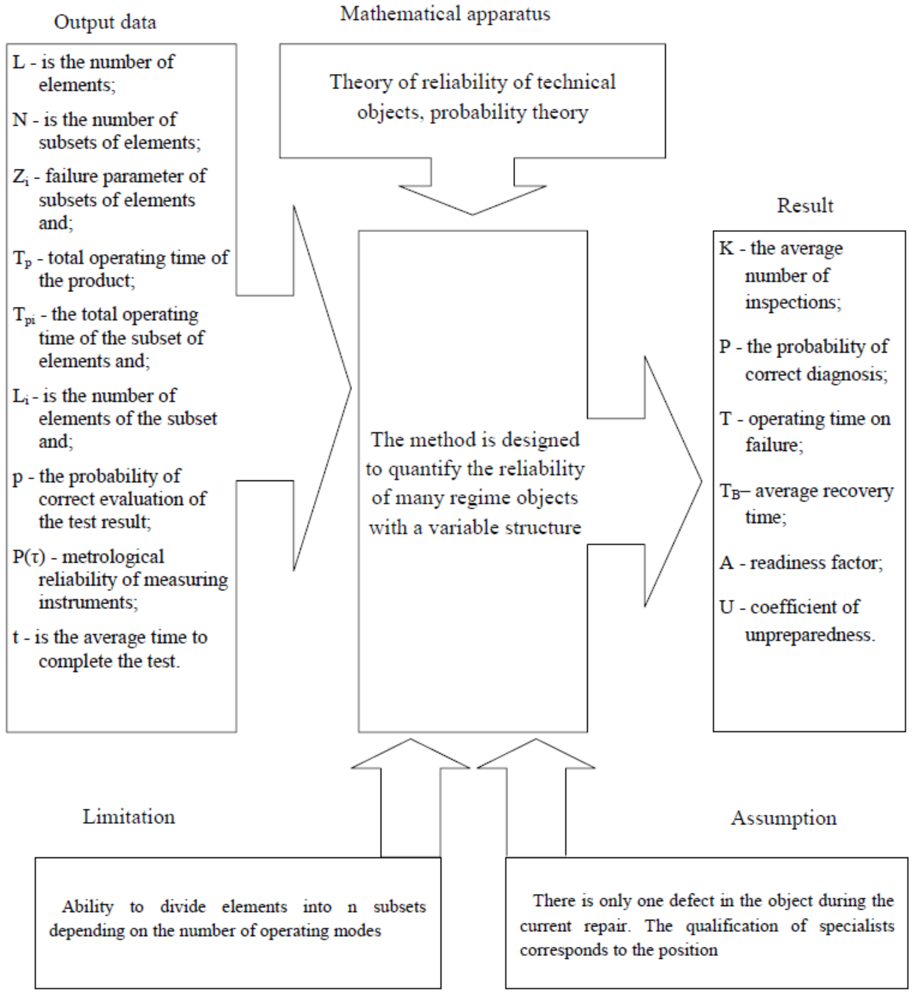

Figure 3: Block diagram of using the method of quantitative assessment of the values of reliability indicators of objects with variable structure

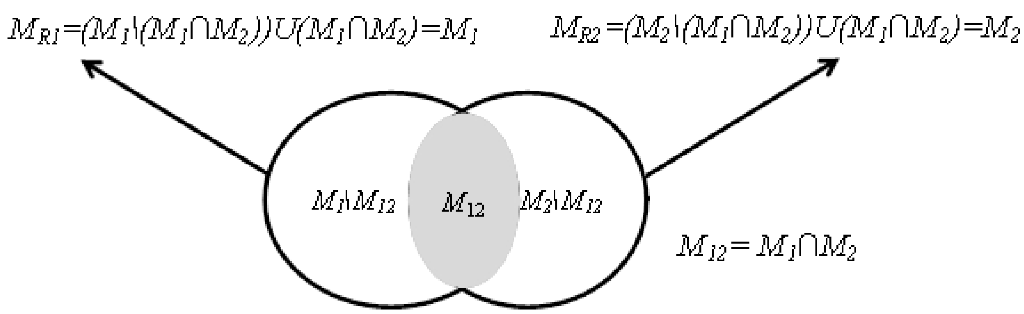

Figure 4: Theoretical-multiple model of a tactical radio station

That is, it was possible to use elements of lower cost to ensure the necessary requirements for the reliability of the radio station during its design and production.

Analysis of the obtained dependences shows that with increasing relative operating time of the radio station in the "reception" mode:

- The operating time for failure decreases, because in this mode most of the elements of radio stations are used (Fig. 5).
- The average recovery time also does not increase significantly as the probability of failure in the receiving part of the radio station increases, and this pattern is maintained at any time during the test *t* (Fig. 6);

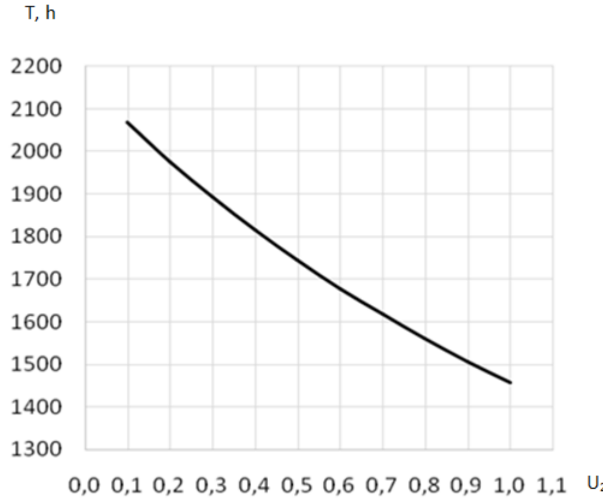

Figure 5: Dependence of operating time on the failure of the radio station on the relative operating time in the mode “reception”

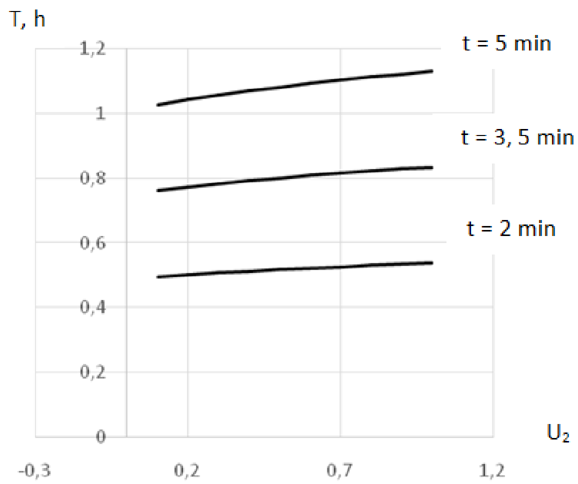

Figure 6: Dependence of the average recovery time of radio stations on the relative operating time in the "reception" mode

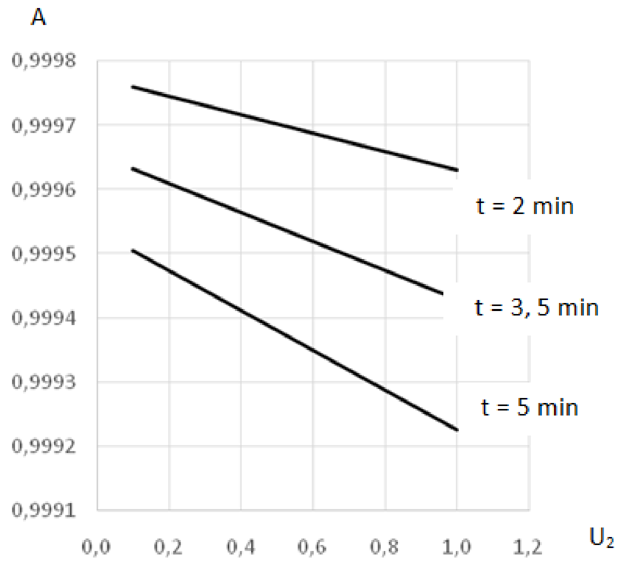

Figure 7: Dependence of the readiness factor of the radio station on the relative operating time in the "reception" mode

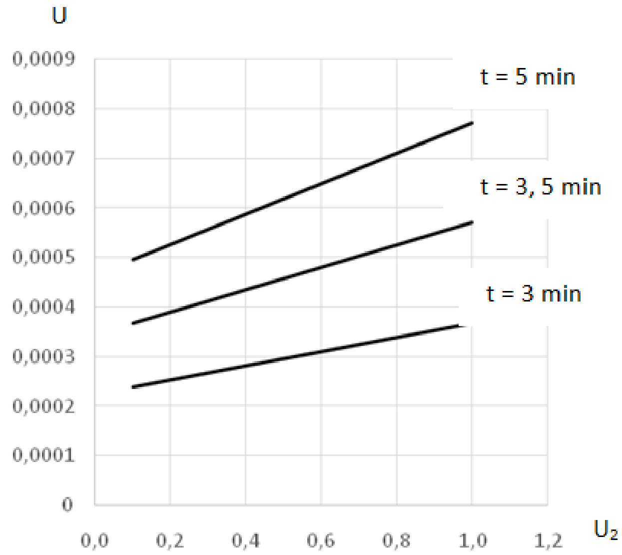

Figure 8: Dependence of the coefficient of unpreparedness of the radio station on the relative operating time in the “reception” mode

Due to the decrease in the value of operating time to failure T and increase the average recovery time T_v also decreases the complex reliability indicator is readiness factor A (Fig. 7) and, accordingly, increases the value of the unpreparedness factor U (Fig. 8).

These trends are maintained at any values of the average time of the test t, moreover, its reduction by improving the skills of performers and improving diagnostic support (the choice of tests with less labor) leads to an increase in the coefficient of readiness (A).

5. Conclusions

1. The paper proposes the improvement of the method of quantitative assessment of reliability indicators of objects with variable structure, the algorithm of realization is given and the advantages over the existing methods are shown.

2. It is established that the use of multi-mode properties, which affects the structure of the object, improves the value of reliability indicators: both the failure time and the average recovery time.

3. The essence of the method improvement and its scientific novelty is to take into account the properties of many modes of the object and the operating time of individual subsets of elements in possible modes when used as intended.

4. Further research should be directed to assess the values of reliability of the communication system, taking into account the possibility of changing its structure during its intended use, especially in training and combat operations, as well as the operating time of individual elements of the system.

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